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FACTORS INFLUENCING AIRCRAFT GROUND HANDLING PERFORMANCE



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FACTORS INFLUENCING AIRCRAFT GROUND HANDLING PERFORMANCE

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Abstract

Problems associated with aircraft ground handling operations on wet runways are discussed and major factors which influence tire/runway braking and cornering traction capability are identified including runway characteristics, tire hydroplaning, brake system anomalies, and pilot inputs. Research results from studies conducted at the Langley Aircraft Landing Loads and Traction Facility, tests with instrumented ground vehicles and aircraft, and a recent aircraft wet runway accident investigation are summarized to indicate the effects of different aircraft, tire, and runway parameters. Several promising means are described for improving tire/runway water drainage capability, brake system efficiency, and pilot training to help optimize aircraft traction performance on wet runways.

Introduction

Research findings and technological advances in recent years have helped alleviate, but not eliminate, the hazards associated with adverse weather aircraft operations. Conversely, better avionics, growth in aircraft fleet, airport/runway congestion, and economics are factors which have increased the frequency of aircraft ground operations during inclement weather. However, to a pilot, happiness is still landing into the wind on a long, clean, dry runway keeping to a minimum the number of challenging situations which can arise during operations on slippery runways with fluctuating crosswinds. Improvements in aircraft braking systems, pilot simulator training programs, and runway surface treatments have tended to increase safety margins but weather-related aircraft accidents still occur such as those last year at Washington, D.C., Boston, and New Orleans. Unpredictable and rapidly

changing weather conditions that may be encountered at a given airport further complicate the problems associated with aircraft takeoff and landing maneuvers. For ground operations under varying rainfall conditions, a large number of interacting runway, aircraft, and atmospheric variables, along with pilot technique, combine to influence the level of aircraft runway performance. A need exists for timely recognition and proper assessment of these parameter combinations that can produce inadequate aircraft braking and directional control performance for a given wet runway situation.

With the introduction of large and fast jet transports into airline service in the late 1950's, various research efforts ^{1 to 27} have been directed towards evaluating the effects on aircraft runway performance due to different rainfall rates, runway characteristics, tire features, and brake system operational modes. Findings from studies conducted at the Langley Aircraft Landing Loads and Traction Facility, tests with instrumented aircraft and ground vehicles, and a recent aircraft wet runway accident investigation are discussed in the following sections of this paper. In addition to showing the effects of several pavement factors and defining the principal causes of wet pavement tire friction degradation and brake system performance anomalies, several promising approaches are identified to help retain adequate tire/pavement friction and brake system efficiency during aircraft ground operations on wet runways.

Pavement Factors

Water Depth

The major factors affecting aircraft wet runway performance are identified in figure 1. This figure indicates that runway water depth and tire/pavement drainage capability combine to define the friction coefficient available to help meet the aircraft stopping and steering requirements. For low rainfall

rates and good drainage conditions this available tire/pavement friction coefficient may remain high; however, for high rainfall rates and poor drainage conditions, the available friction coefficient can drop drastically, especially at the higher aircraft ground speeds. To help promote water drainage, most runways are constructed with a cross slope or crown and coarse, highly textured surface finishes are applied. In general, runway water buildup or surface flooding that occurs during periods of precipitation is directly related to the rainfall intensity, the surface macrotexture (coarse, large-scale, surface roughness), the runway cross slope, and to some extent, the magnitude and direction of surface winds. Pavement flooding is defined as the depth of water that completely covers the top of all surface asperities. Surface winds have been found to affect water drainage path lengths in the flooded portions of the runway and, depending upon the wind magnitude and direction, the amount of surface water can change from that occurring on a calm day. ¹³ From data collected during a comprehensive Texas Transportation Institute study described in reference 10, a relationship was established between rainfall intensity, surface macrotexture, pavement cross slope, and water drainage path length without the presence of surface winds. This relationship, given in figure 2, can be used to calculate the rainfall intensity required to initiate flooding in typical aircraft tire paths on a runway surface for a calm day.

The data shown in figure 2 represent the calculated variation in rainfall rate required to flood to within 4.57 m (15 feet) of the runway centerline. The main gear tires of a B-767 transport airplane would be near this distance from the runway centerline if the airplane was traveling directly down the centerline. Calculations were made for five different cross slopes each having a similar range of macrotexture depths. In general, the figure shows

the increase in rainfall rate needed to flood the surface as a function of cross slope and macrotexture depth. If the depth of pavement macrotexture is small, such as observed in some rubber-coated runway touchdown areas, rainfall intensity required for flooding is low despite appreciable cross slope values. Similarly, the chance of reaching flooded surface conditions for a given rainfall intensity increases with decreasing cross slope. In addition, it can be shown that as the distance from the runway centerline (apex of crown) increases, lower rain rates may produce surface flooding.

Texture

Various research studies²⁸⁻³⁰ have identified two distinct texture classifications, namely, micro- and macrotexture. In general, microtexture consists of the fine, small-scale, surface features such as those found on individual stone particles, whereas macrotexture encompasses the coarse, large-scale roughness of a pavement surface-aggregate matrix. Under rainfall conditions sufficient to initiate flooding on runway surfaces, the bulk water drainage effectiveness of the surface is dependent on macrotexture characteristics. Based on numerous macrotexture depth measurements taken during several research programs⁹ and²⁸ on a wide variety of runway pavement types and conditions using both the grease sample and sand patch measurement methods, surfaces have been classified into the five major pavement groups or classes shown in the table of figure 3. A general description of the different categorized pavement types is given with class I pavement surfaces having the highest macrotexture depth values and class V surfaces having the lowest macrotexture depth values. Since the potential for dynamic hydroplaning, which is described in the tire friction performance section, varies inversely with surface macrotexture, class I pavements are identified as having the least hydroplaning potential whereas class V

pavements are considered to be the most susceptible. Using this pavement classification system as a guide for runway surfaces, airport operators should be encouraged to install class I or II pavement surfaces on runways and if periodic macrotexture depth measurements indicate the runway surface is approaching the class IV category, corrective surface treatments, such as grooving or rubber removal programs, should be implemented. It is also recommended that if a runway or portion of a runway surface is determined to be within class IV or V, adequate and timely notification should be given to pilots particularly during wet weather aircraft landing and takeoff operations.

Although class I pavements have been proven to minimize wet runway friction problems, one recent runway installation created another problem under dry surface conditions which has since restricted aircraft operations to takeoffs only. The photographs in figure 4 illustrate the extent of a tire tread abrasion problem which occurred during three aircraft landing tests on an asphalt-rubber chip seal overlay surface. This operational problem is attributed to the sharp, multi-edged, exposed, stone chips used in the overlay mix combined with the relatively low dry surface friction capability.

Contaminants

The effect of surface water and rubber contaminants on vehicle stopping capability and tire friction performance is shown in figure 5. This evaluation was performed with the NASA-developed diagonal-braked vehicle (DBV) shown in the photograph in figure 5. The brake system diagram illustrates the modification made to implement stable and controlled vehicle performance during the friction measurements at high speed with two diagonal wheels locked and the remaining pair free rolling (unbraked). The DBV wet/dry stopping distance ratios depicted in the bar graphs for different rainfall

rates and surface types were obtained from test runs conducted at the same distance off runway centerline with brake application speed from 98 km/h (60 mph) down to a complete stop. Measurements of surface water depth and

DBV stopping distance during different periods of rainstorm activity on an ungrooved concrete runway with a 1 percent crown reveal a direct relationship between average water depth and stopping distance. As rainfall rates increase, greater water buildup on the runway surface occurs which decreases tire friction performance as reflected in the increased DBV wet/dry stopping distance ratios. A further increase in runway slipperiness was found near the end of the runway which was contaminated by rubber deposited during aircraft tire spin-up following touchdown. The buildup of the rubber coating on runway surfaces tends to reduce pavement texture and hence, degrade tire friction particularly under wet conditions. The cross-hatched DBV stopping distance increment shown in figure 5 illustrates the effects of rubber contamination on the ungrooved concrete runway slipperiness measurements for different rainfall rates. Also included in the figure are comparable DBV measurements made on other grooved and ungrooved runways under artificially wetted (truck) conditions where the average water depth was 0.5 mm (0.02 in.). The longer DBV wet/dry stopping distance ratios measured on the ungrooved asphalt runways compared to the concrete surfaces are the result of lower surface macrotexture. Fortunately, successful methods ³¹ have been developed to remove the rubber deposits on runway surfaces using high pressure water and now many major airports regularly schedule runway rubber removal treatments.

Tire Friction Performance

Viscous and Dynamic Hydroplaning

During aircraft ground operations in wet weather, a water removal or drainage problem is created at tire/pavement interfaces. The runway surface

water encountered by the moving aircraft tires must be rapidly expelled from the tire/pavement contact area or the viscous and dynamic water pressures that build up with increasing ground speed will significantly reduce tire friction performance. Research studies ²⁸⁻³⁰ have shown that the slope of a tire friction-speed gradient curve is primarily a function of the surface macrotexture, and the magnitude of the friction at a given speed is related to the surface microtexture. Hence, an assessment of both surface micro- and macrotexture characteristics is necessary to fully relate tire friction performance to pavement texture.

The principal forms of these wet pavement tire friction losses, namely, viscous and dynamic hydroplaning and reverted rubber skidding, are illustrated in figure 6. The speed regime, pavement and tire condition, and tire operating mode that contribute to loss in tire friction are identified together with the factors that tend to alleviate their occurrence. Viscous hydroplaning or thin-film lubrication results from the inability of the tire to penetrate and disrupt the very thin residual fluid film left on the pavement after the majority of the trapped water has been displaced from the tire footprint. In this case, the pressure buildup within the tire/pavement interface is due to fluid viscous properties. Smooth tires operating on wet smooth pavements are particularly susceptible to this type of tire hydroplaning.

During dynamic hydroplaning, a buildup of hydrodynamic pressure between tire and flooded pavement occurs as the square of vehicle speed. ² When this hydrodynamic pressure exceeds the tire-pavement bearing pressure, a wedge of water penetrates the tire contact area and the tire footprint is partially or totally detached from the pavement surface. Under total dynamic hydroplaning conditions, tire friction capability is reduced to near zero because of the inability of the fluid to support significant shear forces. It should

be noted that for many wet pavement aircraft operations, reduced tire friction performance may occur from both viscous and dynamic fluid pressure buildup resulting in combined viscous/dynamic hydroplaning. ¹³

The contact pressure developed between tire tread and pavement establishes the escape velocity of bulk water drainage from beneath the tire footprint. High pressure tires can expel surface water more readily from the footprint than low pressure tires. When the aircraft ground speed equals or exceeds the escape velocity of water drainage from the footprint, choked water flow occurs. The tire has now reached the state of total dynamic hydroplaning. Test results ², ¹², and ¹³ indicate that the critical aircraft ground speeds required for this total hydroplaning condition to occur on flooded (runway water depth is greater than tire tread groove depth) pavements with an unbraked tire are approximately:

$$\text{Spin-down (Rotating tire) speed, knots} = 9 \sqrt{\text{Infl. pressure, psi}}$$

and

$$\text{Spin-up (Nonrotating tire) speed, knots} = 7.7 \sqrt{\text{Infl. pressure, psi}}$$

For the nonrotating tire case (as at aircraft touchdown), Langley track test results shown in figure 7 illustrate the delay in tire spin-up following touchdown on a flooded surface until the test carriage speed decreased to approximately 93 knots. It is important that pilots be aware that the lower hydroplaning spin-up speed, rather than the high hydroplaning spin-down speed, represents the actual tire situation for aircraft touchdown on flooded runways.

Reverted Rubber Skidding

The third form of tire friction loss, reverted-rubber skidding, is named for the appearance of the tire tread skid patch after a prolonged locked-wheel skid. It is believed that friction-generated heat within the skidding tire/pavement contact area is sufficient to produce steam and cause the tire

tread rubber to revert back to its uncured state.¹² and ¹⁸ The soft gummy reverted rubber forms a seal around the tire footprint periphery and the entrapped steam and water significantly reduce braking and cornering capability. This hypothesis would also explain the distinctive (steam cleaned) mark left on the pavement in the tire path as shown in the aircraft accident photographs in figure 8. Evidence from this aircraft wet runway skidding accident as well as several others indicates that once started, reverted rubber skidding results in very low tire/pavement friction which persists down to very low speeds. With tire operation in a nonrotating mode, the loss of tire cornering capability for directional control is possibly a greater problem, considering runway geometry, for pilots to overcome than the low braking performance. Providing and maintaining runway surfaces with high macrotexture and good drainage characteristics is very important in alleviating the occurrence of this aircraft tire friction loss as well as those associated with tire hydroplaning.

Aircraft Landing Performance

During aircraft ground operations, pilot techniques and control inputs together with certain aircraft parameters including aerodynamics, engines, brake system, and landing gear configuration interact to determine how much of the available tire pavement traction is utilized for stopping and directional control purposes. The influence of speed, tire tread condition, and pavement surface macrotexture on aircraft braking performance is illustrated in figure 9. These data were obtained during instrumented CV990 aircraft braking tests⁸ conducted at NASA Wallops Flight Center on a unique research runway which features a variety of pavements selected to provide a wide range of surface macrotextures. A portion of each of these different pavements was modified with installation of 6 x 6 x 25 mm (0.25 x 0.25 x 1-in. pitch) transverse grooves. For dry concrete conditions, the measured aircraft

effective braking friction coefficient level indicated in figure 9 did not vary significantly with tire tread design or surface configuration but some decrease was observed with increasing speed. The effect of speed was much more pronounced on the wet ungrooved surface and these data indicate that ~~the rib-tread design provided a significant improvement compared with the~~ smooth tire data. The calculated hydroplaning spin-down speed of 114 knots noted in figure 9 is based on a tire inflation pressure of 1103 kPa (160 lb/in²). On the similarly wetted grooved concrete, the transverse runway grooves produced substantially greater aircraft braking friction levels with both tire treads than were shown by the wet ungrooved surface data. These aircraft braking performance data on wet runways also suggest that the effects of tire tread wear are secondary to the effects of surface grooving because of the greatly enhanced tire/pavement water drainage capability available on grooved runways.

Antiskid Behavior

The brake system is the primary means for stopping the aircraft. The development and use of antiskid control systems designed to minimize tire skidding and prevent wheel lockups during braking has substantially enhanced aircraft braking performance and stopping capability. Most antiskid systems employ touchdown and locked-wheel protection features in the brake control logic circuits to prevent brake pressure application to a nonrotating wheel as at touchdown or as the result of low tire/pavement friction conditions causing wheel lockup. The proper performance of these systems, however, depends on accurate inputs of aircraft ground speed and instantaneous braked wheel angular velocity data coupled with efficient mechanisms for reducing and reapplying hydraulic pressure to each wheel brake unit. Effective antiskid brake control operation also requires positive wheel spin-up

accelerations after tire touchdown and following brake pressure release during antiskid cycling. Since wheel spin-up characteristics are directly influenced by the friction generated between the tire and the runway, brake

control behavior can be significantly compromised during aircraft operations under adverse weather conditions and at high ground speeds. The precision of braked wheel control by the antiskid deteriorates when low tire traction causes low wheel spin-up accelerations. Certain pilot inputs, such as full brake application before the wheels reach synchronous aircraft speed, can also adversely affect brake control because the logic circuits do not receive the correct aircraft ground speed reference value. ¹⁴

Aircraft Test Results

An example of such anomalous antiskid brake control operation following touchdown is given in figure 10. These time history data collected during wet runway tests with a large jet transport aircraft ³² illustrate the antiskid brake control response of the inboard wheels on a four-wheel bogie main landing gear to brake applications that occurred prior to and after full wheel spin-up during landings. For brake application prior to full wheel spin-up, it is apparent from figure 10 that the ground speed reference assumed by the skid-control logic circuit for the front wheel is well below the actual aircraft speed. The low wheel spin-up accelerations following brake pressure release during each braking cycle, combined with the low ground speed reference, prevented the front wheel from attaining synchronous aircraft speed until approximately 30 seconds into the landing rollout. By that time, the aircraft speed had decreased sufficiently to cause high wheel spin-up acceleration and the proper ground speed reference signal was acquired. Subsequently, braked wheel motion was satisfactorily controlled down to the aircraft stop point. The much faster recovery of aircraft synchronous speed

by the rear tandem wheel (Figure 10) reflects the benefit of path clearing by the front tandem wheel which produces a less slippery surface for the trailing wheel.

Figure 10 also includes wheel angular velocity data obtained during a second aircraft landing in which brakes were applied after the wheels reached full spin-up. These braked wheel responses suggest that the pilot should delay brake application during landings on wet runways to allow the skid-control logic system sufficient time to acquire an accurate ground speed reference. The considerably reduced tire skidding experienced during this landing compared to the data collected when brakes were applied early suggests improved aircraft stopping performance and reduced tire wear. It should be noted that a comparison of the braking effectiveness demonstrated by the two landings is not justified because the tests were made at different aircraft gross weights and brake application speeds.

Comparative aircraft braking effectiveness data is presented in figure 11 for three landing tests conducted with a B-727 aircraft equipped with an antiskid brake system. These test results, ²² which show the variation in effective braking friction coefficient with speed for one dry and two wet runway landing cases, illustrate the significant effect that tire/runway friction and braked wheel control have on aircraft braking performance. For the dry and wet runway landings (cases 1 and 2) conducted with sufficient tire/runway friction to permit braked wheel control without locking the wheel, a continuous increase in friction was measured as the aircraft speed decreased. As expected, significantly higher aircraft braking effectiveness was obtained during the dry runway landing compared to the wet runway landing. The second wet runway landing, case 3, was made with an average surface water depth about twice that measured for case 2. This greater runway water depth

resulted in much lower tire/runway friction and all four main gear wheels locked following brake application. The subsequent skidding produced a reverted rubber patch on the tire such as shown in the photograph in figure 11. With the development of reverted rubber skidding, the aircraft braking effectiveness was substantially reduced with little change in friction throughout the landing speed range. The calculated aircraft stopping distance for case 3 is approximately twice that found for case 2. Of equal concern, a locked (nonrotating) wheel cannot provide stabilizing forces necessary for directional control. Analogous low tire friction results were also obtained during Langley track tests ⁶ when prolonged tire skidding on a wet surface produced reverted rubber in the tire contact patch.

Additional insight into the lack of directional control as well as reverted rubber skidding caused by nonrotating tires was obtained during a recent investigation of a T-38 aircraft landing veeroff accident which occurred at night during a moderate rainstorm. A left-to-right crosswind component caused the pilot to land the aircraft at a crab angle slightly right of runway centerline. The accident aircraft landing runout track, identified by white marks visible on the runway surface, is shown in figure 12 together with photographs of the ungrooved, low textured (class V), concrete runway surface, the main landing gear (MLG) tire skid patches, and the damaged aircraft. Fortunately, the pilot escaped injury even though the nose and right main landing gear failed and the right wing tip was sheared off subsequent to the aircraft leaving the right shoulder of the runway, traversing a relatively soft soil surface, and coming to rest on an intersecting paved taxiway. During the investigation which followed the accident, the estimated aircraft touchdown point near the runway intersection was found to be a water ponding area with water depths measured up to 13 mm (0.5 in.). Additional evidence

and factors which tend to support the belief that possibly the MLG tires did not spin up following touchdown include the fact that the aircraft touchdown speed was significantly higher than the calculated tire hydroplaning spin-up speed of 119 knots, the surface white marks from the MLG tires commenced when the aircraft exited the deeply flooded portion of the runway and continued to the runway shoulder edge, and only one skid patch, showing evidence of tread rubber reversion in the aft portion, was found on each MLG tire. Knowing that he was landing on a wet runway, the pilot did not apply wheel braking during the aircraft runout on the paved runway and yet, reverted rubber skidding evidently occurred. Inspection of the aircraft wheel brake assemblies revealed no abnormalities and no indication of dragging brake operation. In all other documented aircraft accident/incident cases involving reverted rubber skidding, the pilot had employed wheel braking during the aircraft runout which contributed to locked wheel operation.

Concluding Remarks

The principal weather, aircraft, runway, and pilot factors which combine to affect aircraft ground handling performance during wet runway operations have been reviewed. This review included: identifying a relationship established between rainfall rate and runway water depth; defining the major forms of tire friction losses; classifying pavement surfaces by macrotexture depth and hydroplaning potential; and evaluating antiskid brake system performance. Research results from studies conducted at the Langley Aircraft Landing Loads and Traction Facility, tests with instrumented ground vehicles and aircraft, and a recent aircraft wet runway accident investigation were presented to illustrate the effects of various parameters on aircraft braking effectiveness. These findings underscore the complexity and variability which characterizes

aircraft wet runway operations. Research efforts, however, have revealed several promising means, such as the use of runway grooving and frequent rubber removal treatments, which offer improved tire/runway water drainage capability and hence, contribute to safer aircraft operations. In reviewing the factors influencing aircraft wet runway performance, several approaches or needs have also been recognized to alleviate the severity of the problem including: continued updating of pilot education and training procedures; implementation of procedures for monitoring slippery runway conditions and identifying severity to the pilot; improvement in antiskid brake system performance; and prompt remedial treatment of runway surface drainage problems.

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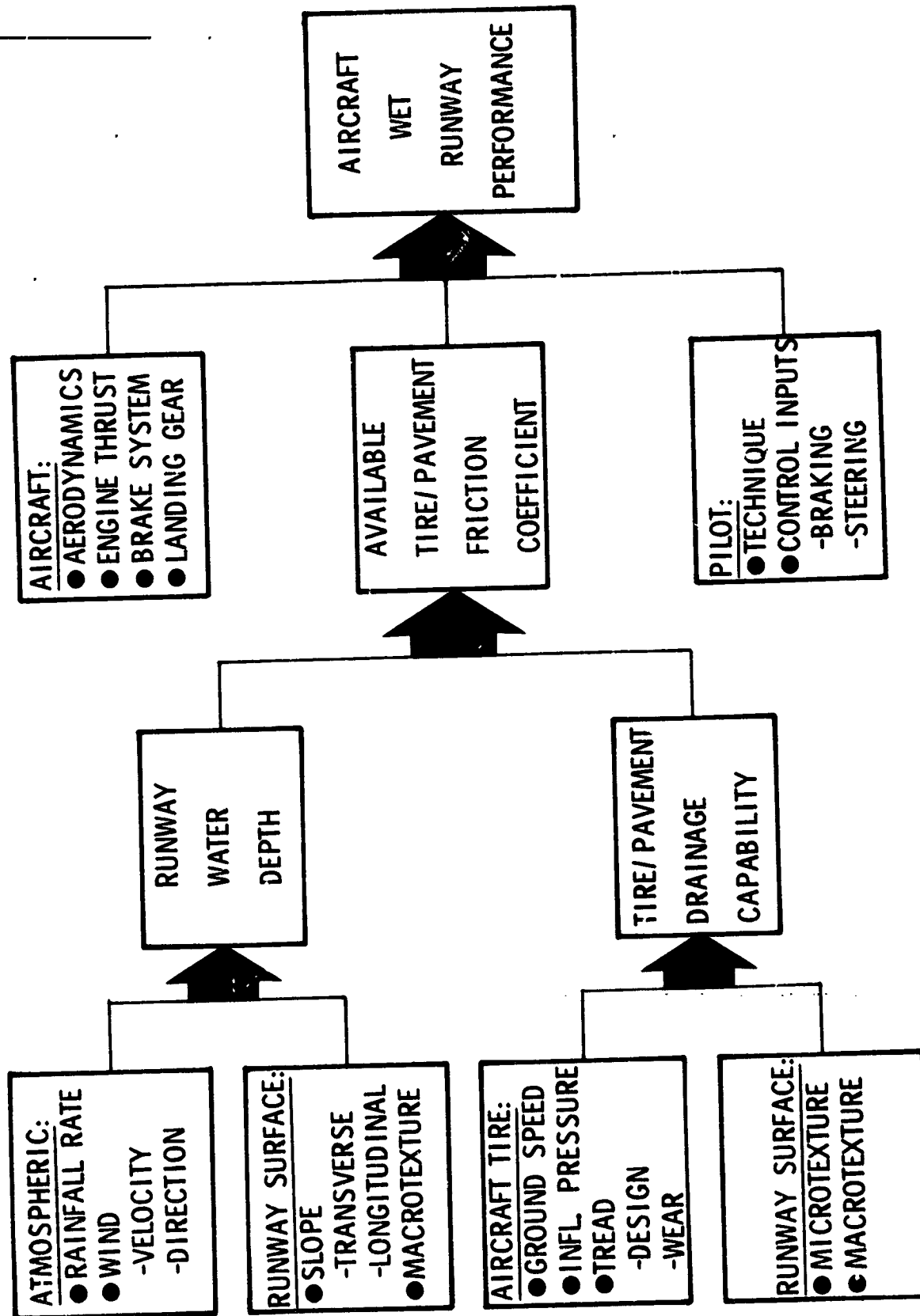


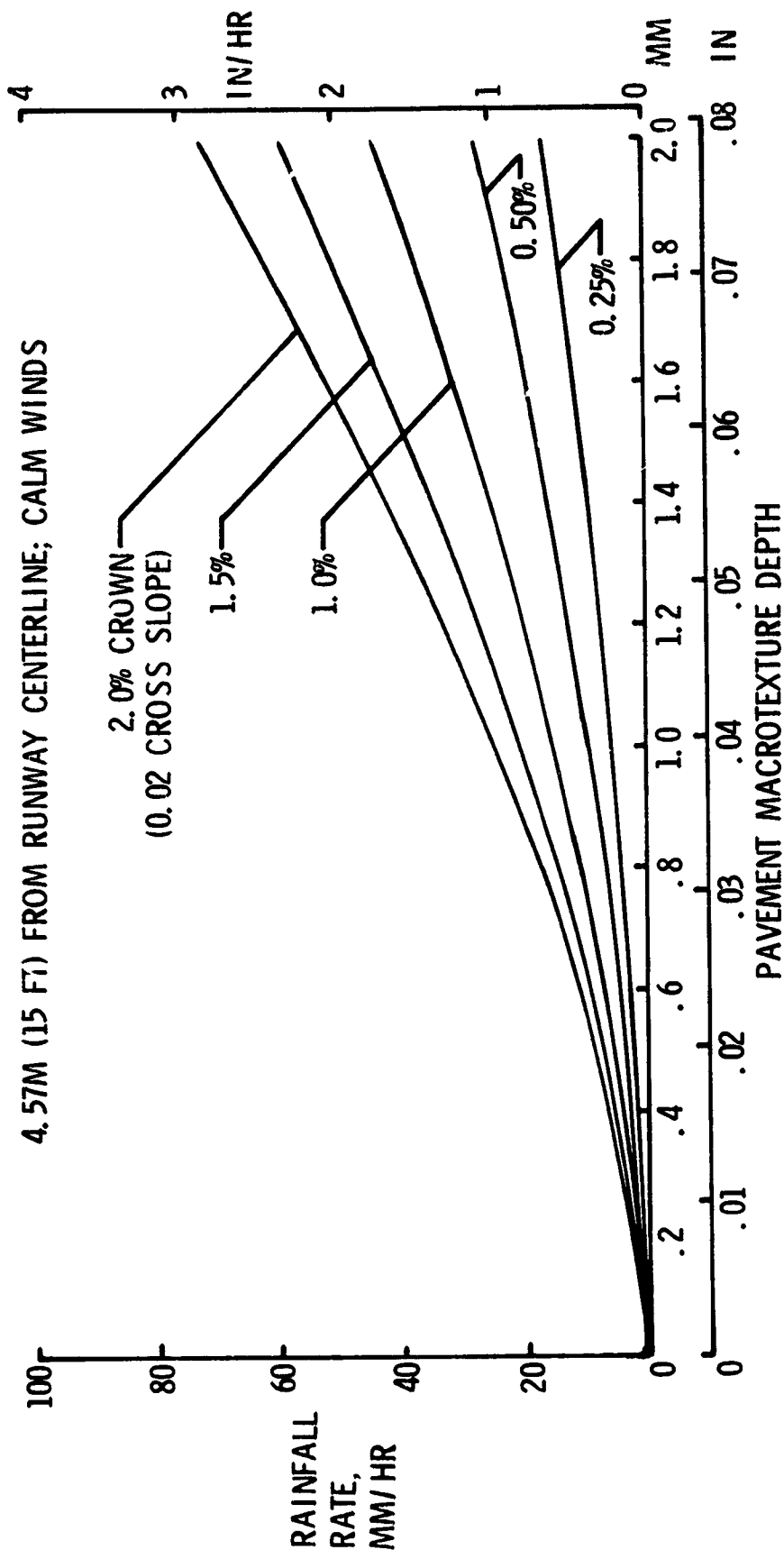
Figure 1.- Factors affecting aircraft wet runway performance.

$$\text{RAINFALL RATE} = K \left[\frac{(\text{MACROTEXTURE DEPTH})^{.89}}{(\text{DISTANCE FROM RUNWAY } \text{E})^{.43} \left(\frac{1}{\text{CROSS SLOPE}} \right)^{.42}} \right]^{1.695}$$

(FROM REF. 10)

WHERE:

K = 1253 for metric units; 15430 for U.S. Customary units

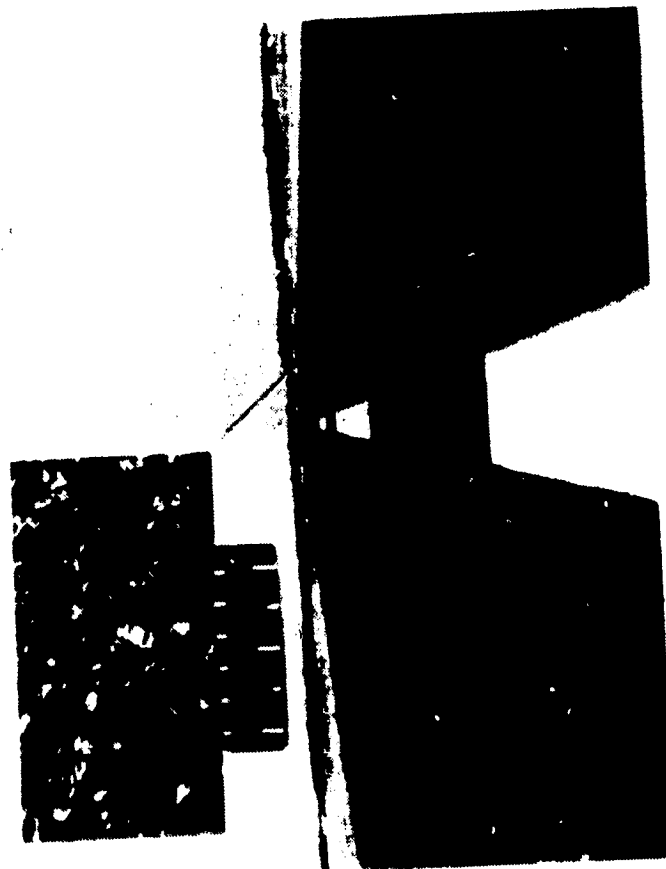


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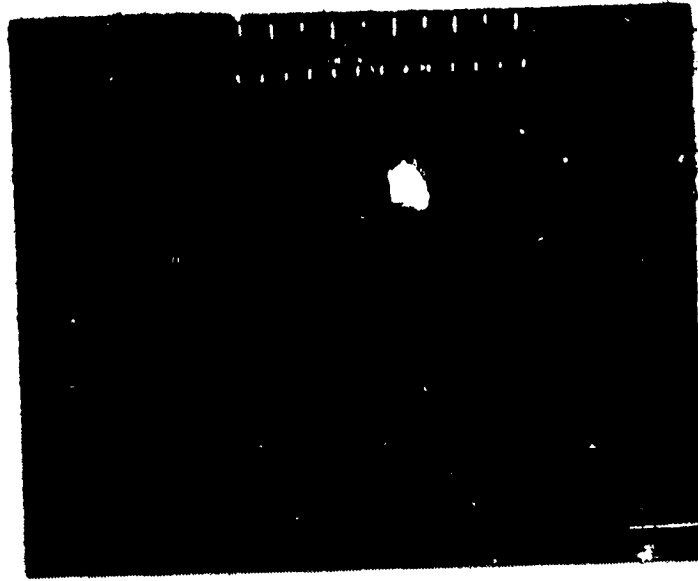
Figure 2.- Calculated rainfall rate required for flooding runway surfaces in typical transport aircraft main gear tire path.

CLASS	TYPE OF SURFACE	HYDROPLANING POTENTIAL	MACROTEXTURE DEPTH, MM (IN.)	
			GREASE SAMPLE METHOD	SAND PATCH METHOD
I	DEEP GROOVING	LOW	>1 (0.04)	>1.8 (0.07)
	OPEN TEXTURE			
II	POROUS FRICTION COURSE	POOR	1 (0.04) TO 0.5 (0.02)	1.8 (0.07) TO 0.9 (0.035)
	SHALLOW GROOVING			
III	SCORING AND WIRE COMBING	FAIR	0.5 (0.02) TO 0.3 (0.01)	0.9 (0.035) TO 0.6 (0.024)
	SOME LARGE AGGR. ASPHALT			
IV	HEAVILY TEXTURED CONCRETE	GOOD	0.3 (0.01) TO 0.1 (0.004)	0.6 (0.024) TO 0.25 (0.01)
	SOME MIXED-GRADATION AGGREGATE ASPHALT			
V	LIGHTLY TEXTURED CONCRETE	HIGH	<0.1 (0.004)	<0.25 (0.01)
	SOME WORN AND TRAFFICKED MOST SMALL AGGR. ASPHALT			
	VERY LITTLE TEXTURE			
	PAINTED AND RUBBER COATED SOME HEAVILY TRAFFICKED			

Figure 3.- Classification of pavement surfaces by hydroplaning potential and macrotexture depth.



ASPHALT-RUBBER CHIP SEAL OVERLAY SURFACE



TREAD ABRASION FOUND ON
B-737 AIRCRAFT MAIN GEAR TIRE

Figure 4.- Example of high macrotexture runway surface causing aircraft tire tread abrasion problem.

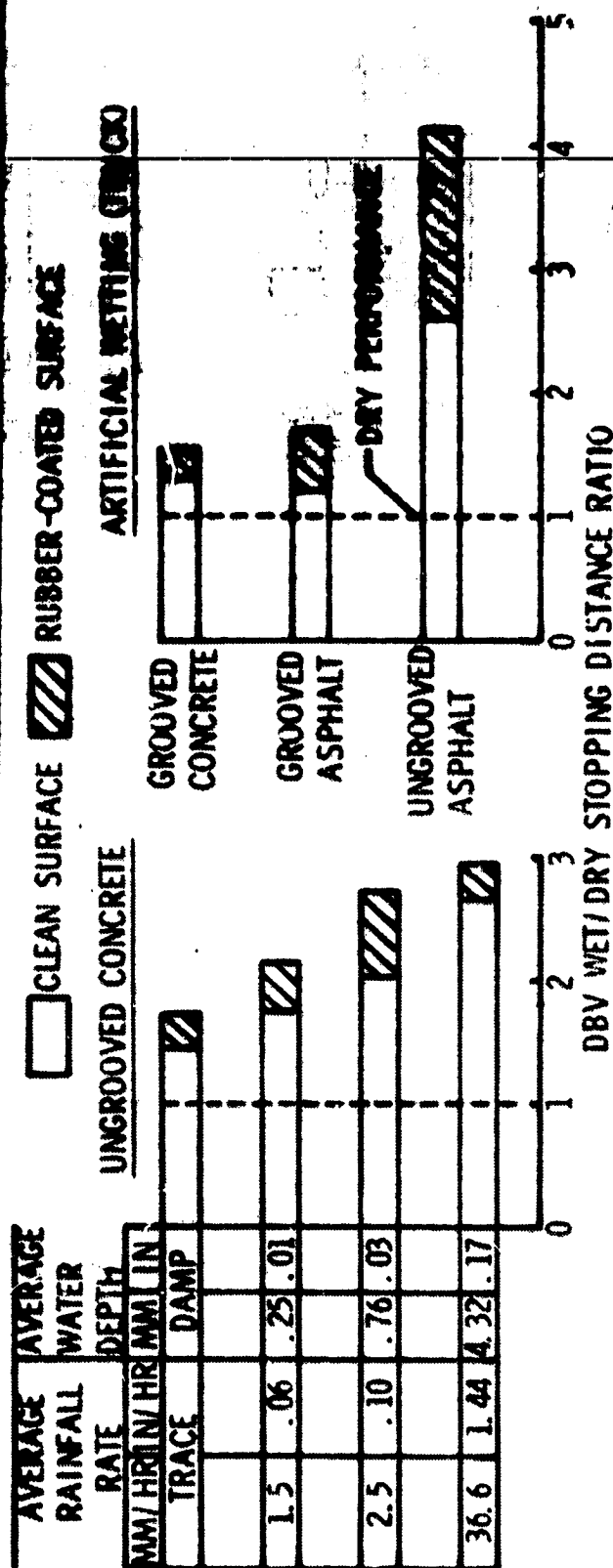
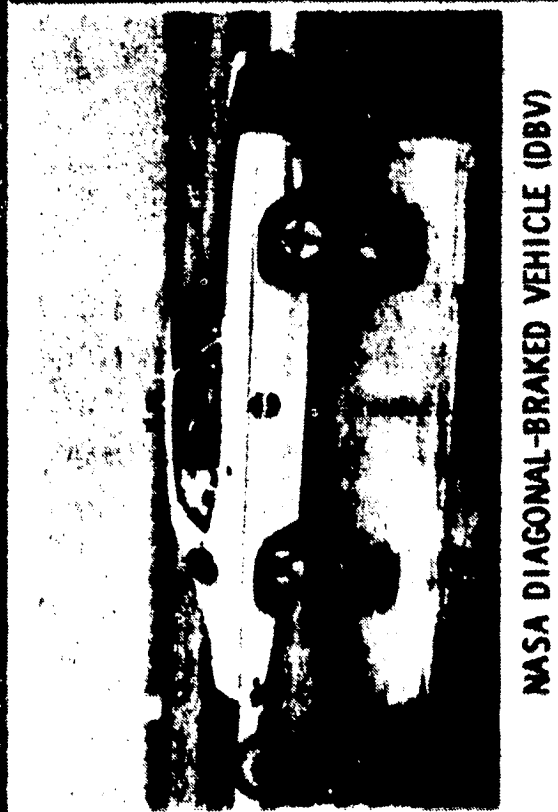
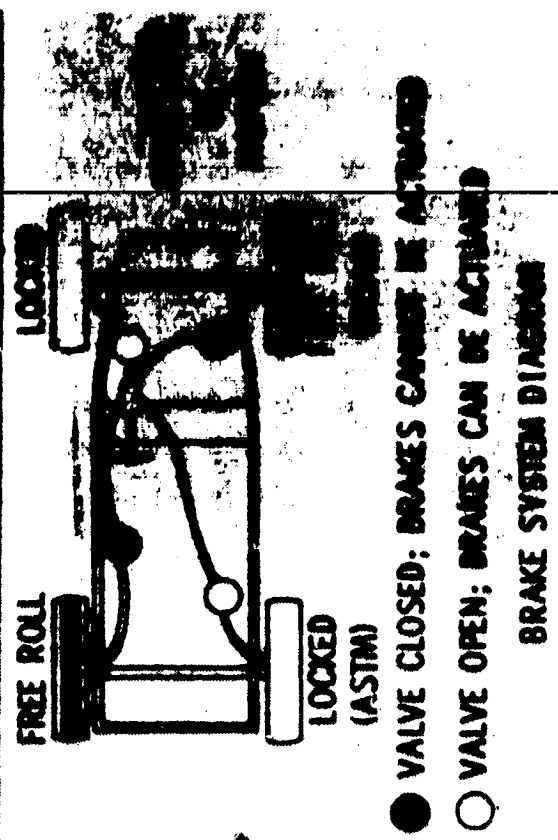


Figure 5.- Effect of surface contaminants on diagonal-braked vehicle stopping performance.

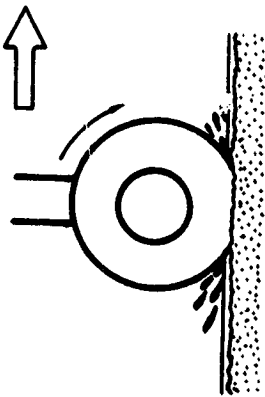
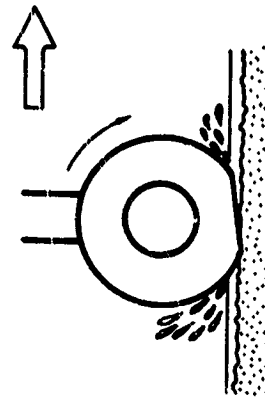
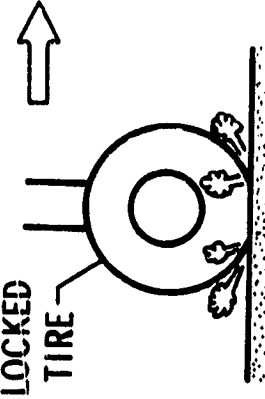
CAUSES	HYDROPLANING			REVERIED RUBBER SKIDDING
	VISCOUS	DYNAMIC		
				
CONTRIBUTING FACTORS	DAMP OR WET PAVEMENT MEDIUM TO HIGH SPEED POOR PAVEMENT TEXTURE WORN TIRE TRFAD	FLOODED PAVEMENT HIGH SPEED LOW TIRE PRESSURE WORN TIRE TREAD	WET OR FLOODED PAVEMENT HIGH SPEED POOR PAVEMENT TEXTURE DEFICIENT BRAKE SYSTEM	
	PAVEMENT MICROTEXTURE PAVEMENT GROOVING GOOD TREAD DESIGN	PAVEMENT MACROTEXTURE PAVEMENT GROOVING INCREASED TIRE PRESSURE GOOD TREAD DESIGN	GOOD PAVEMENT TEXTURE PAVEMENT GROOVING IMPROVED ANTISKID	
ALLEVIATING FACTORS				

Figure 5.- Principal causes of wet pavement tire friction losses.

DC-9 MAIN GEAR, RIB-TREAD TIRE; INFLATION PRESSURE, 965 kPa (140 LB/IN.²)
 AVERAGE WATER DEPTH, 5 MM (0.2 IN.)

TIRE HYDROPLANING SPIN-UP SPEED = 91 KNOTS

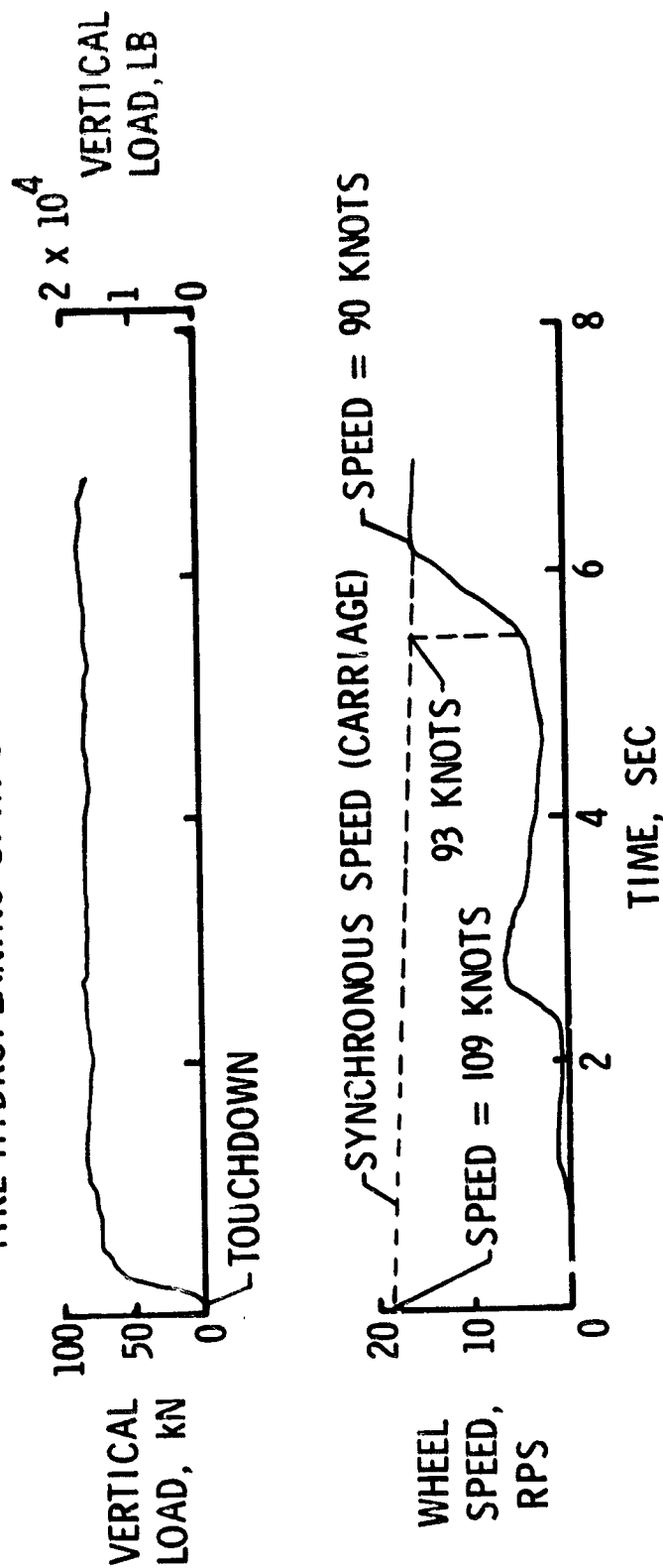
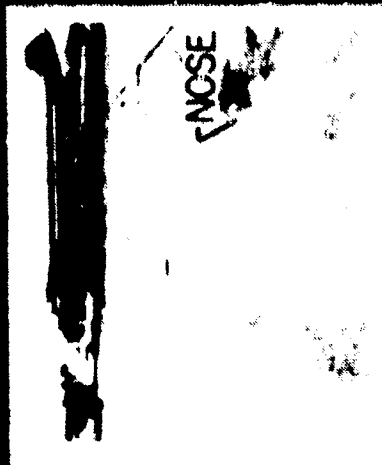


Figure 7.- Delayed wheel spin-up at touchdown on flooded runway test surface at Langley track facility.

ORIGINAL PAGE IS
 OF POOR QUALITY

HYDROPLANING ACCIDENT - WET RUNWAY 4 ENGINE
JET TRANSPORT



NOSE

LEFT MAIN AND NOSE
TIRE TRACKS



RIGHT MAIN TIRE
TRACKS



MAIN LANDING GEAR TIRE WITH
REVERTED RUBBER SKID PATCH

Figure 8.- Example of reverted rubber skidding during aircraft wet runway landing.

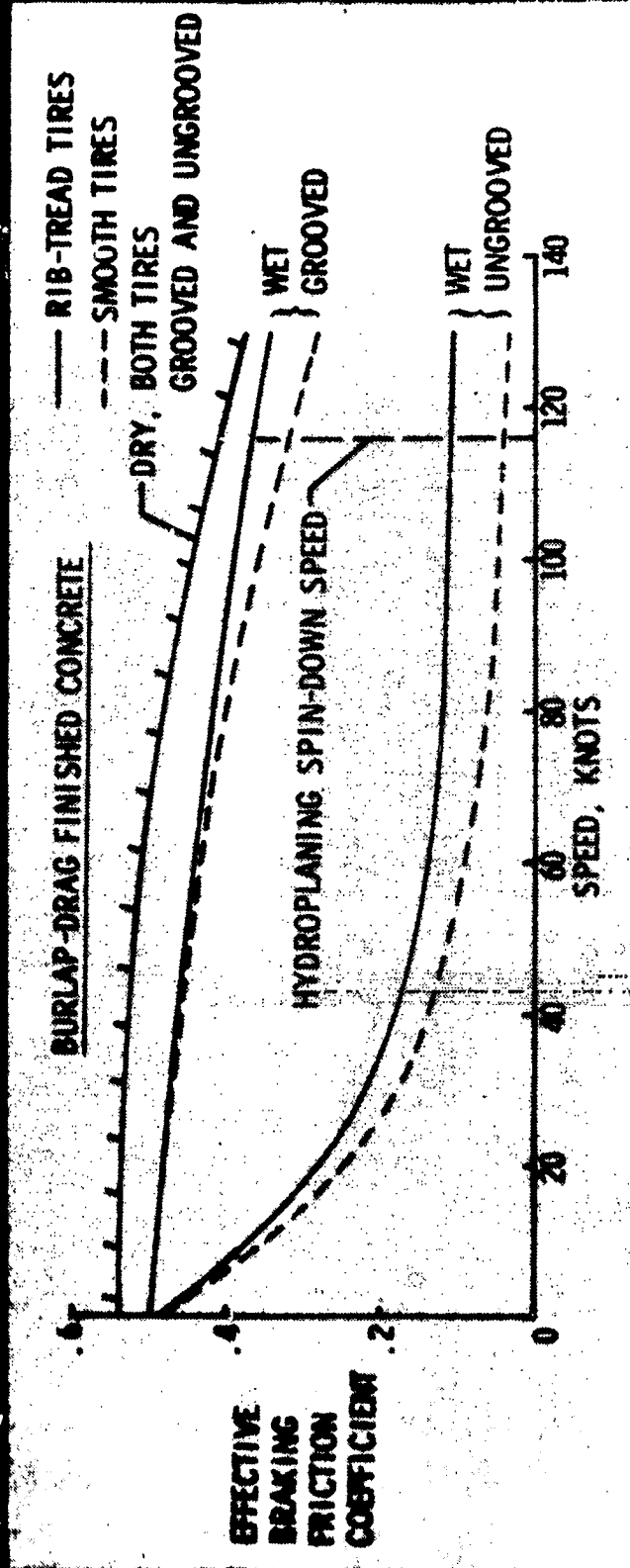


Figure 9.- Effect of tire tread design and pavement surface condition on CV990 aircraft braking friction.

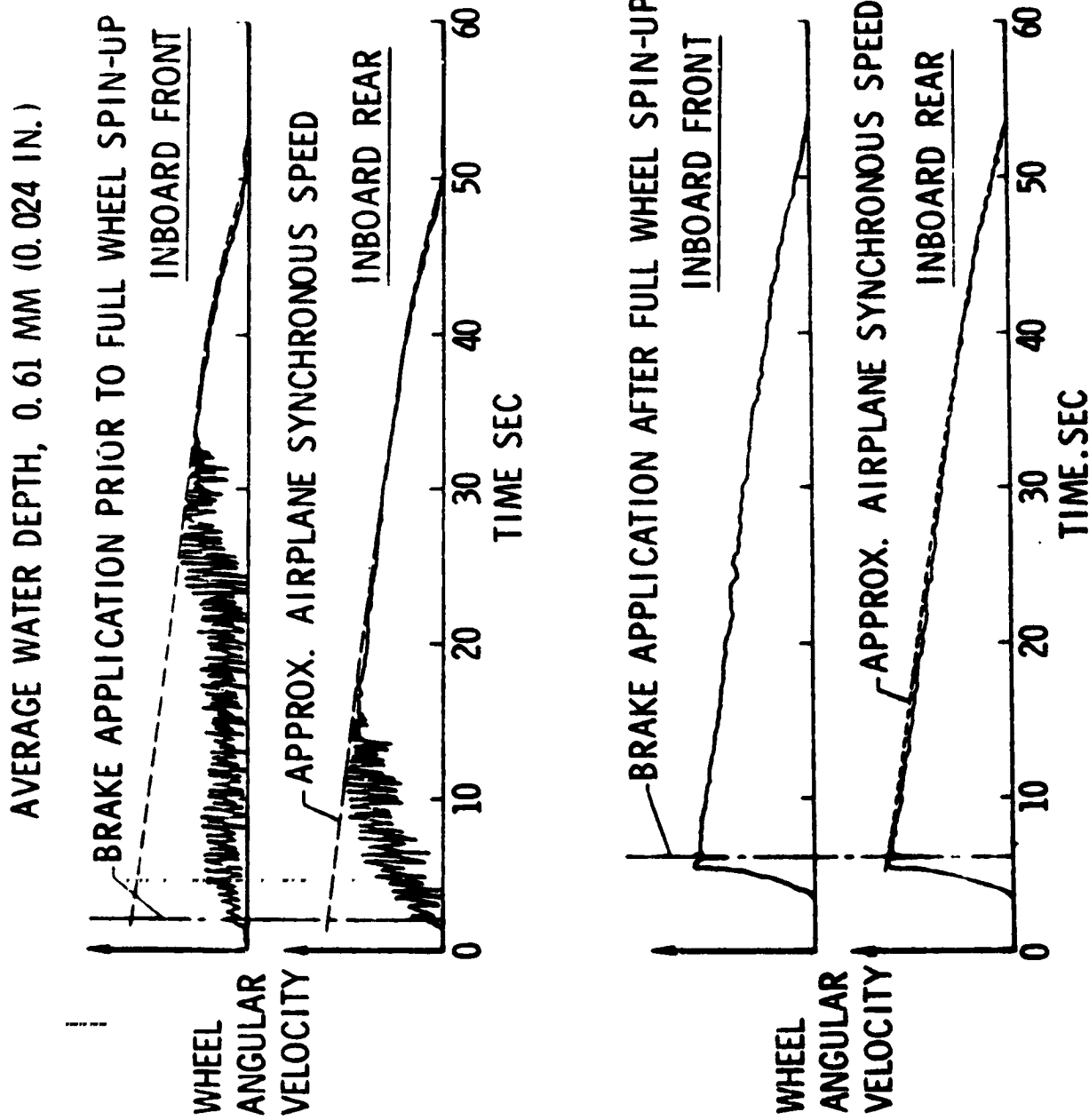


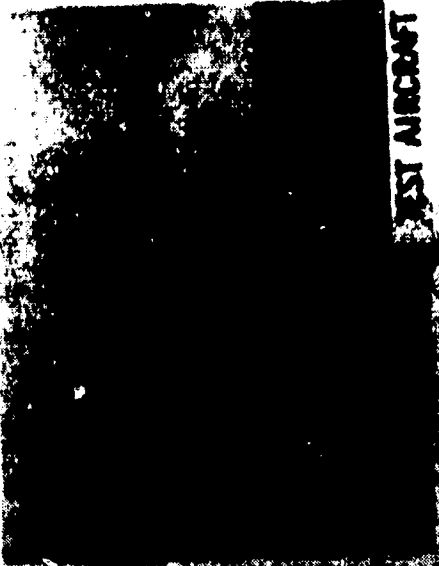
Figure 10.- Aircraft braked wheel responses for antiskid brake application prior to and after full wheel spin-up during landings on wet surface.

UNREINFORCED CONCRETE

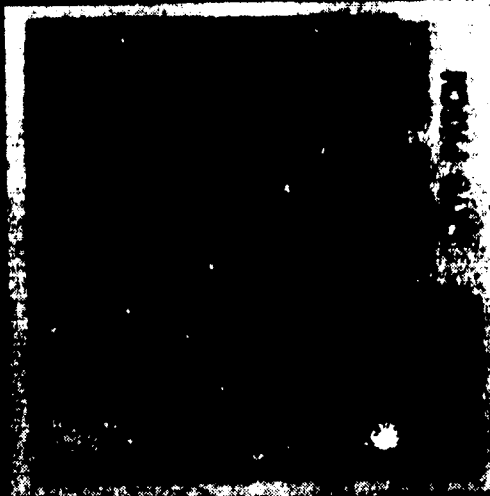
CASE 1, 10%
REINFORCED CONCRETE

CASE 1, 10%
REINFORCED CONCRETE

CASE 1, 10%
REINFORCED CONCRETE

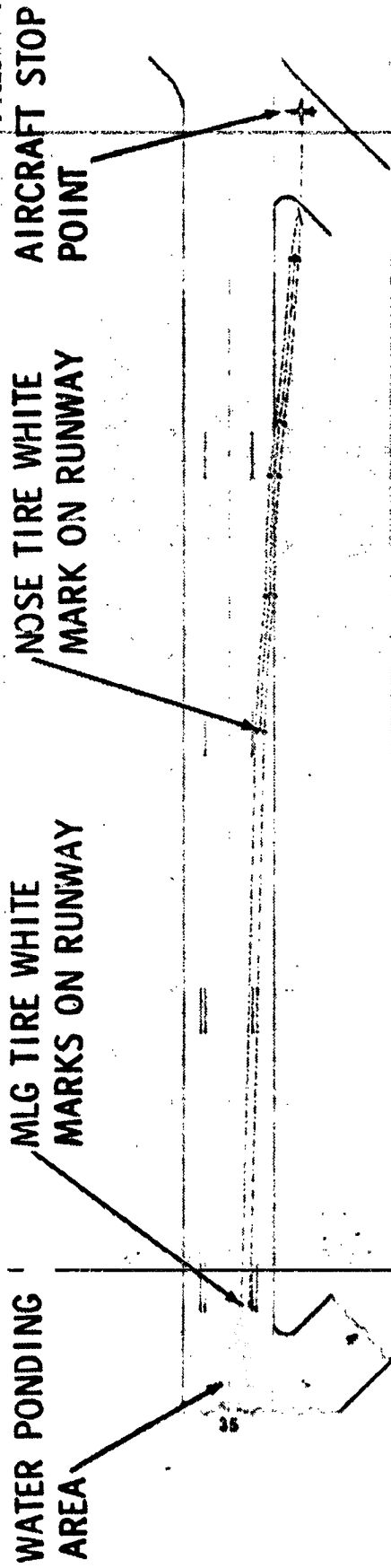


TEST AIRCRAFT



TEST AIRCRAFT

Figure 1. Comparison of drilling performance for a test aircraft.



ACCIDENT AIRCRAFT RUNOUT TRACK

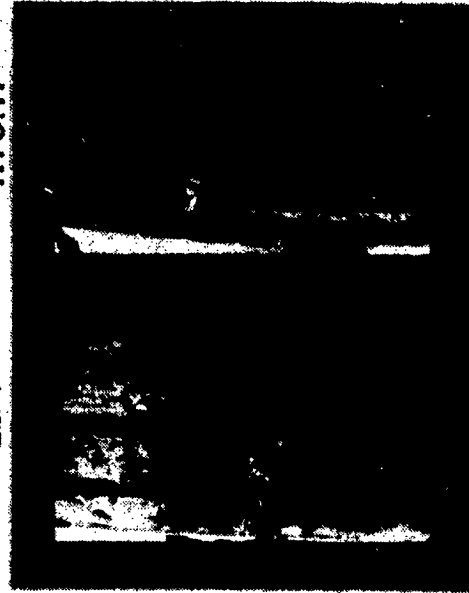
MLG TIRE TRACKS

LEFT

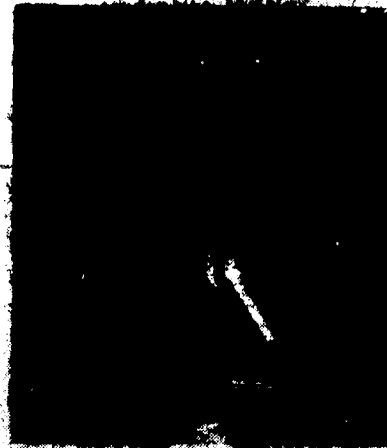
RIGHT



RUNWAY SURFACE



SKID PATCHES ON MLG TIRES



DAMAGED AIRCRAFT

Figure 12.- Aircraft wet runway landing accident with reverted rubber skidding occurring without wheel brake application.